European Regional Development Fund

D 2.3.1. VIABILITY STUDY REPORT

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1. INTRODUCTION

Following the results obtained during Activity 2.1 (Materials for Metal Additive Manufacturing) and 2.2 (Manufacturing, post-processing and characterisation of demonstrators), this document intends to analyse the technological and economic viability of each pilot developed during ADDITOOL project.

The main objective of this study is to compare and analyse the results achieved during the development of the Metal Additive Manufactured (MAM) use cases, with the conventional processes that are applied in the real environment of the SMEs. Concretely:

- Study of the conventional manufacturing process that SMEs use for the manufacturing of the target tooling part.
- Technological viability analysis for the implantation of additive manufacturing processes appropriates for the manufacturing of the components.
- Economical study of the implantation of MAM or modification of the processes adding MAM and comparison of part cost to obtain the use case study.
- Benefits that MAM offered to the manifesting of the component.

The demonstrators manufactured by ADDITOOL partners have been tested in each company (SMEs associated partners), directly on their production site. The goal is to validate or not the relevance of using MAM technologies in their production processes and compare with the performance of the original part.

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2. TECHNOLOGICAL AND ECONOMICAL STUDY

2.1. Pilot FR1- LAUAK

Background

The pilot parts offered by the associated partner LAUAK are two “control jigs” type of tools to control the good shape of an aircraft metal sheet.
These two tools are originally mass machined, from a block of 40CMD8T steel pre-treated at 110MPa, steel which benefits from good machinability and adequate mechanical performance.

The tolerances on the functional surfaces comply with the ISO 2768 mK standard with a Ra of 3.2µm. On the entire part, the tolerances are 0.1mm +/-0.05.

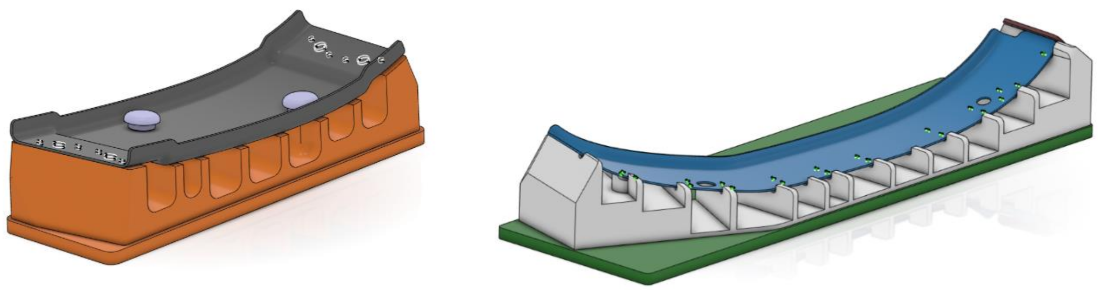


Figure 1 : LAUAK parts D54516181 & D54516298

Part D54516181 (in orange in Figure 1) is produced internally by the LAUAK company, which has all the means necessary to manufacture the part:

- Material supply lead time: 1 week – Block of 40CMD8T (200 x 100 x 50mm)
- Machining: Between 15h and 20h and some cutting tools
- Cost price: 1750€ including study / material supply / manufacturing / three-dimensional control.
- Life cycle: 1000 parts

Part D54516298 (in grey in Figure 1) is produced internally by the LAUAK company, which has all the means necessary to manufacture the part:

- Material supply lead time: 1 week – Block of 40CMD8T (600 x 200 x 100mm)
- Machining: more than 100h and a lot of cutting tools

- Cost price: 3500€ including study / material supply / manufacturing / three-dimensional control.
- Life Cycle: 1000 parts

Objectives of the pilot

The objective of this pilot will be threefolded:

- Keep a similar cost price for manufacturing.
- Keep an equivalent or reduced "time to market".
- Improve performance (increase life) while reducing machining costs and time.

To meet these objectives, here is the method that was used:

- Characterization of the material: raw material as well as the manufactured part, for each technology
- Simulation of temperatures and residual stresses during the manufacturing
- Manufacture these two tools with 3 different technologies:
    - DED Wire Laser: Part D54516181 – Manufacturing of the complete part
    - DED Wire Arc: Part D54516298 – Manufacturing of the complete part with a redesign.
    - DED Powder Laser: Part D54516298 – Reloading to improve hardness only on the top of the part (only part in contact with the aircraft part)
- 3D scan of the parts to see any deformations before heat treatment and after machining.
- Thermal treatment
- Machining
- Controls and Tests in real conditions of use

Material selection

The material used by LAUAK (40CMD8T) being very poorly weldable, a change of material was agreed to make it manufacturable and improve its mechanical performance, in particular its hardness. The improvement in hardness will thus allow a consequent extension of the service life.

After a study on the available materials, we selected 15CrMnMoV5-4-9-3 (15CDV6) for the manufacture of these parts.

	Designation	Re (Mpa)	Rm (Mpa)	A5 (%)	Hardness (HRC)	Available for Wire D1,2mm	Available for DED Powder 40-110microns	Weldability
Original	40CMD8 (40CrMnMoS8-6)	850	1000	11	32 - 34	No	?	No
Proposal	EN4334 (15CrMnMoV5-4-9-3) // AIR 9117 : 15CDV6	930	1080 - 1280	10	42	Yes		Yes
Proposal	EN4331 (25CrMnMo4-2-2) // AIR 9117 : 25CD4	750	880 - 1080	12	46	Yes		Yes
proposal	INVAR 36	679	717	5.5	98 (RCB)	YES	YES	YES

Figure 2 : Material selection

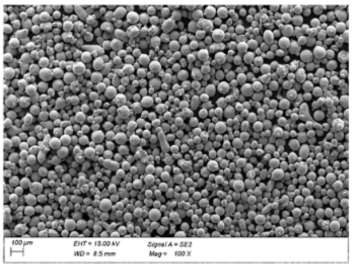
The Figure 2 shows that the 15CDV6 has better performances than the original material, with +10HRC and +80MPa on the Re. This material is available in wire therefore adaptable for the DED Wire Arc process and with good absorption with a laser in the infrared therefore possible for the DED Wire Laser.

The objective of this pilot being the comparison of 3 processes (DED Wire Laser, DED Wire Arc and DED Powder Laser), it was necessary to develop a powder of 15CDV6 having the same chemical characteristics as the wire, see Figure 3.

CEIT: FR1_LAUAK

15CDV6 Powder

10 Kg of gas atomized 15CDV6 (AIR 9117) powder. +44-106 µm particle size. [EN4334: 15CrMnMoV5-4-9-3]



Physical properties	
$\rho_{pycnometry}$ (g/cm³)	7,68 +/- 30
$\rho_{apparent}$ (g/cm³)	4,31
ρ_{TAP} (g/cm³)	4,54
Flow rate (s/50g)	0,33

Interstitial level (wt.%)	
O	0,0126
N	0,0014
C	0,122
S	0,049

Specifications. Chemical Composition 15CDV6 (wt.)

	C	Mn	Si	Cr	Mo	V	P	S	P+S
Min-Max	0,12-0,15	0,80-1,10	Max 0,20	1,25-1,50	0,80-1,00	0,20-0,30	Max 0,02	Max 0,0015	Max 0,04
Type	0,14	1,00	0,15	1,40	0,90	0,25	0,003	0,001	<0,040

Figure 3 : Development of 15CDV6 powder

The powder characterization results are available in deliverable D2.1.1 Report on material for MAM.

Viability study

As detailed previously, three technologies were used to manufacture these two pieces:

- DED Wire Laser
- DED Wire Arc

- DED Powder Laser

The advantage of using DED Wire Laser technology is to have a Near Net Shape part as close as possible to the final geometry to limit the machining part and have a high yield/deposition rate (higher than powder technologies).

The DED Wire Arc makes it possible to have a Near Net Shape that is more approximate than the DED Wire Laser but a yield/deposition rate much higher than the other two processes.

Finally, the DED Powder Laser is very useful for the hardfacing/reloading part or the functionalization of a part. Since the deposition rates are relatively low, there is not necessarily any interest in manufacturing these two parts with this technology. In this case, it was profitable to machine a block of AISI 1045 which has the advantage of having a very low cost and very easy to machine and weld, then to add material (15CDV6) to the useful areas in order to increase surface hardness.

<u>DED Wire Laser</u>

The manufacture of the LAUAK D54516181 part was carried out with the following means:

- Robot COMAU NJ165
- Effector PRECITEC CoaxPrinter
- Laser TRUMPF TrueDisk 6000 – 6kW
- Wire SelectArc *15CrMnMoV5-4-9-3* // Diameter 1.2mm

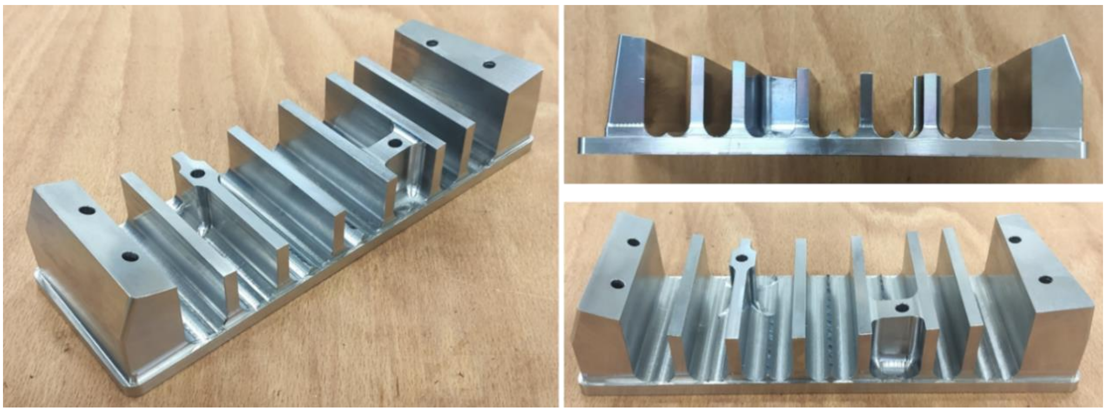


Figure 4 : Part manufactured with DED Wire Laser

The part has been checked by LAUAK and fully meets the requirements. The hardness has been improved compared to the original part, which suggests an increased service life. Also, the metallurgical properties are good, with performances similar or even superior to a forged block, see Deliverable D2.1.1 Report on material for MAM.

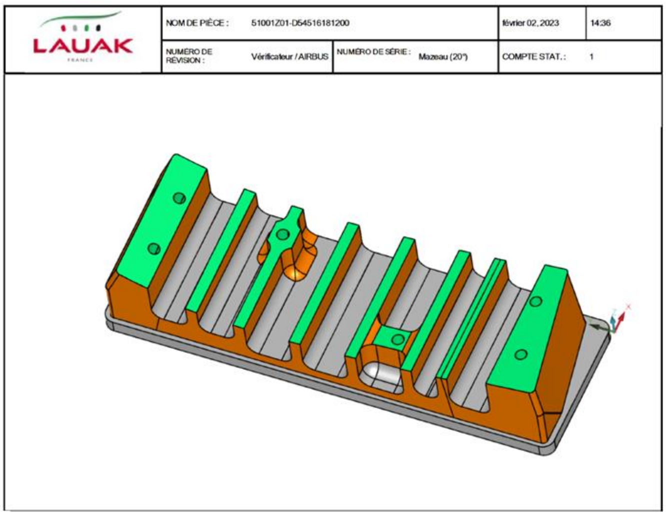


Figure 5 : Control of the part by LAUAK

It is difficult to compare the costs of manufacturing a part in two places and with two different modes of business operation. However, here is a price estimate based on actual outsourcing expenses.

Description	Price	Delay
Substrate supply 300 x 150 x 10mm	95€	3 weeks (can be greatly reduced)
Wire supply (2.2kg deposited)	215.5€ (98€/kg)	3 weeks (can be greatly reduced)
Programming	112.5€ (900€/day)	1h
Fabrication	412.5€ (1500€/day)	2.2h
Scan & Thermal treatment	500€	8h
Machining	1620€ (outsourced) (may be greatly reduced if done in-house)	5h machining – 1 week subcontracting
Control	-	1 week (realised by LAUAK)
Total	**2955.5€**	**5 weeks including 4.9 weeks in procurement and subcontracting**

Here is what is important to note in the manufacture of this piece with DED Wire Laser technology:

- Programming time and manufacture of the Near Net Shape in less than 4 hours.
- The cost of 2955.5€ takes into account the 1620€ of machining subcontracting and which can be greatly reduced.
- The machining time of the Near Net Shape is only 5h instead of more than 20h from a mass machined. This inevitably leads to a considerable reduction in tool wear.
- Procurement time can be greatly reduced for a production company.
- The metallurgical properties are similar or even superior to forging, see document D2.1.1 Report on material for MAM.

DED Wire Arc

The manufacture of the LAUAK D54516298 part was carried out with the following means:

- Robot FANUC Arcmate 120iC
- CMT Fronius TPSi
- Wire SelectArc *15CrMnMoV5-4-9-3* // Diameter 1.2mm

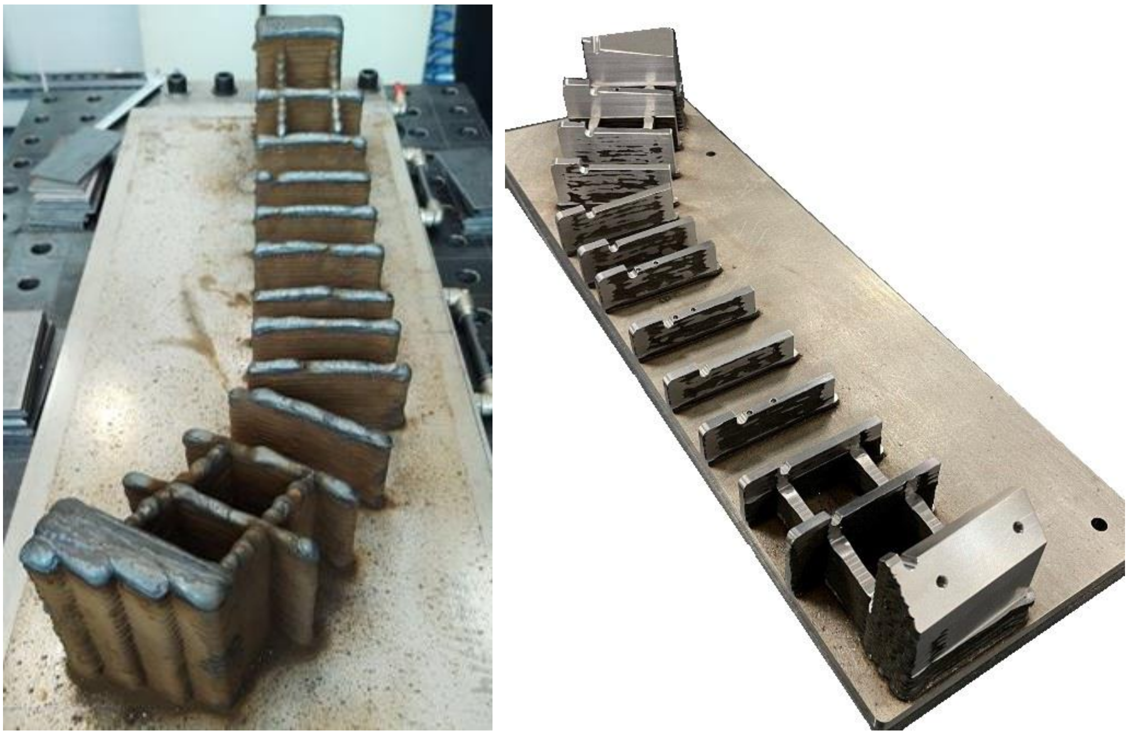


Figure 6 : Part manufactured with DED Wire Arc

The part has also been checked and fully meets the needs of LAUAK. The hardness has been improved compared to the original part, which suggests an increased service life. Also, the metallurgical properties are good, with performances similar or even superior to a forged block, see Deliverable D2.1.1 Report on material for MAM.

Pc	NOM DE PIÈCE : 51001201-D54516298200	février 14, 2023	09:54
	NUMÉRO DE RÉVISION : / NUMÉRO DE SÉRIE : AVEC LAMAGE	COMPTE STAT. : 1	

DEFAUT DE FORME 0.2 DES FACES DE DESSUS

⌖	MM	AX	VAL. NOM.	+TOL	-TOL	MESU	DÉV	HORS TOL
LOC1 - PNT1		T	0.000	0.100	-0.100	0.024	0.024	0.000
LOC2 - PNT28		T	0.000	0.100	-0.100	-0.003	-0.003	0.000
LOC3 - PNT27		T	0.000	0.100	-0.100	-0.010	-0.010	0.000
LOC4 - PNT26		T	0.000	0.100	-0.100	0.037	0.037	0.000
LOC5 - PNT25		T	0.000	0.100	-0.100	0.037	0.037	0.000
LOC6 - PNT24		T	0.000	0.100	-0.100	0.092	0.092	0.000
LOC7 - PNT23		T	0.000	0.100	-0.100	0.088	0.088	0.000
LOC8 - PNT22		T	0.000	0.100	-0.100	0.045	0.045	0.000
LOC9 - PNT21		T	0.000	0.100	-0.100	0.050	0.050	0.000
LOC10 - PNT20		T	0.000	0.100	-0.100	0.017	0.017	0.000
LOC11 - PNT19		T	0.000	0.100	-0.100	0.019	0.019	0.000
LOC12 - PNT18		T	0.000	0.100	-0.100	0.002	0.002	0.000

Figure 7 : Control of the DED Wire Arc part

In the same way as in DED Wire Laser, it is difficult to compare the manufacturing costs of a part in two places and with two different business operating modes. However, here is a price estimation based on actual outsourcing expenses.

Description	Price	Delay
Substrate supply 650 x 250 x 14 mm	194 €	1 week (it can be in stock)
Wire supply (5.9 kg deposited)	527 € (90 €/kg)	3 weeks (it can be in stock)
Programming	112.5 € (900 €/day)	1 h
Fabrication	1312.5 € (1500 €/day)	7 h (2.3 h of dwell time that can be reduced)
Scan	100 €	1 h
Machining	3470 € (outsourced) (may be greatly reduced with training)	3 weeks subcontracting (problems with distortions)
Control	-	1 week (realised by LAUAK)
Total	**5716 €**	**8 weeks (it can be reduced to 1 week)**

Here is what is important to note in the manufacture of this piece with DED Wire Arc technology:

- Time to program and manufacture the Near Net Shape in 7 hours including 2.3 hours of dwell time – with 3.3 kg/h deposition rate.
- The cost of 5716€ includes the 3470€ of subcontracting in machining and which can be greatly reduced if more training to machine NNS part would be done.
- The machining time of the Near Net Shape is only 20 hours instead of more than triple or even quadruple from a mass machined. This inevitably induces a considerable reduction in tool wear – In total, more than 40 kg of material savings.
- Delivery time can be greatly reduced for a production company to 1 week maximum.
- The metallurgical properties are similar or even superior to forging, see document D2.1.1 Report on material for MAM.

- The great reduction of material savings (more visible for the bigger part), lower machining work and the possibility of the use of these technologies for repair, contributes to sustainability.

DED Powder Laser

The manufacture of the LAUAK D54516298 part was carried out with the following means:

- DED Trumpf Trucell 300 + 3kW Disk laser.
- Powder feeder with coaxial head
- developed by CEIT as part of ADDITOOL – same chemistry as the wire
- Block machined from AISI 1045

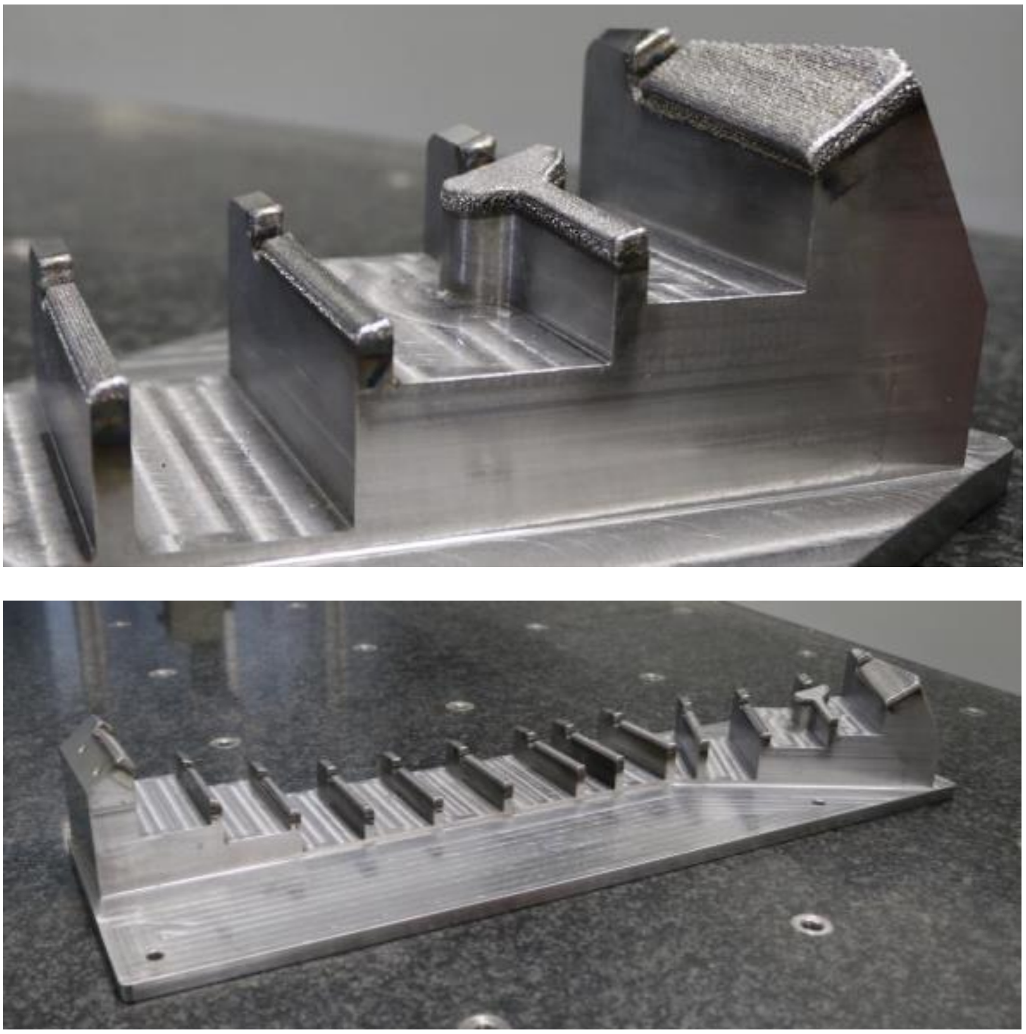


Figure 8 : Part manufactured with DED Powder Laser

This part was not checked because it was only partially machined to serve as a demonstrator for the project. On the other hand, the hardness has also been improved compared to the original part, which suggests an increased lifespan – 39HRC on the surface and 18HRC in the substrate. In terms of costs, here is an estimate:

Description	Price	Delay
Substrate supply 570 x 175 x 95 mm	148 €	1 week
Powder supply (0,33kg deposited with 70% deposition efficiency)	85.8 € (200€/kg)	4 weeks (can be greatly reduced)
Programming	726 € (900€/day)	6,5 h
Fabrication	311.25 € (1500€/day)	1.66 h
Machining	1,829.00 € (outsourced) (may be greatly reduced if done in-house)	7h machining – 4 weeks subcontracting
Control	-	1 week (realised by LAUAK)
Total	**3,100.00 €**	**9 weeks including 4 weeks in procurement and 4 weeks in subcontracting**

Here is what is important to note in the manufacture of this piece with Powder Wire Laser technology:

- Near Net Shape manufacturing time in less than 2 hours.
- The cost of 3100€ takes into account the 1,829.00 € of machining subcontracting and which can be greatly reduced.
- The cost of raw material is greatly reduced with this process. Moreover, this process allows a repair if the tool has been worn and has lost its dimensions.

2.2. Pilot PT1-MOLDETIPO

Background

Conformal cooling channels, that is, cooling channels that are designed to closely match the part geometry to enhance their cooling, have already been attained by MAM technologies in moulds for plastics, with significant results.

In these applications, the degree of optimization achieved in the thermal performance of the mould translates into a much higher production rate, reduces production costs, and therefore, gives a significant added value to the mould.

The part proposed is an insert for an injection mould, used in the manufacturing of a bi-material part (POM + Thermoplastic Elastomer). This insert works in conjunction with another insert, as pair to shape the part. However, this latter will not be studied, for the sake of simplicity. The mold itself has 2 sets of inserts. In conjunction with a mould rotation, this allows the injection of 2 materials simultaneously.

The inserts work as side movements, highlighted in the mould – Figure 10. The mould is designed to produce 2 parts in each shot. As mentioned, only one insert was produced by hybrid manufacturing, while the other insert in the pair and the second set of inserts were produced by conventional means. This enabled a comparison of their performances without having to switch the inserts. The components have a base (grey in the figure) which, because of its geometry, could be manufactured using either a hybrid approach, or a conventional approach. In the latter case, each insert can be manufactured as 2 separate parts, which are later assembled, or the base can be conventionally manufactured and then the active part can be built on top of it, using an additive manufacturing technology.

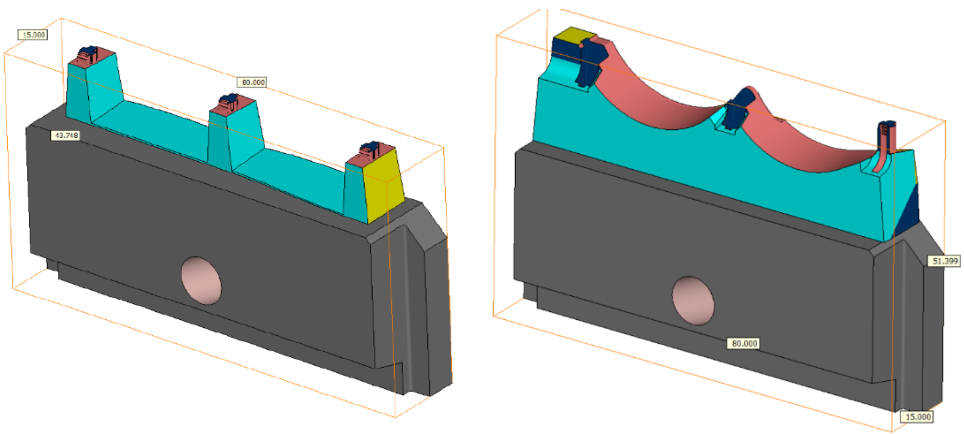


Figure 9. The inserts that work in conjunction to shape the part. Only the insert on the right was studied and produced by hybrid manufacturing - SLM + machining.

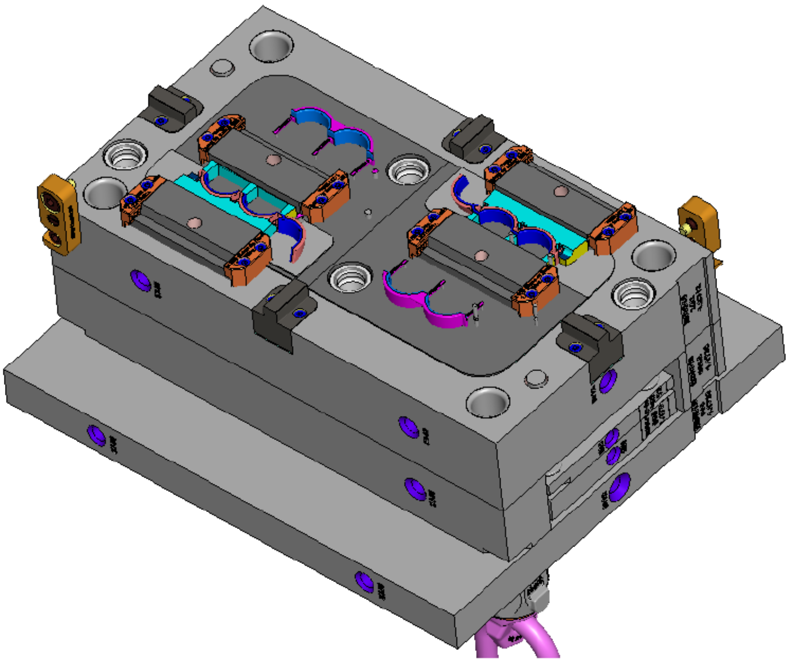


Figure 10. The mould where the inserts are assembled. The light blue inserts are sliding mechanisms. One of them is to be manufactured by an hybrid process.

Objectives of the pilot

The case study proposes to optimize the cooling of the insert, by adding conformal cooling channels. The small dimension of the zone to be cooled in this case makes the manufacturing of conformal cooling channels very difficult for conventional processes. This is enabled by manufacturing it by Laser Powder Bed Fusion (L-PBF).

The purpose of this pilot is to optimize the design and manufacturing methodologies of mould inserts for the optimization of cooling, by employing advanced modelling including topological optimization, thermal simulation, hybrid manufacturing and non-destructive testing. Cost analysis will also be addressed. All outputs shall be compared to conventional manufacturing solutions.

Material Selection

The material selected for the pilot is a commercial tool steel in powder form - Böhler W360 - as an alternative to the standard H13 steel. This is because the W360 is designed for machines without a heated bed, which is the case of the Trumpf TruPrint 1000 that was be used to manufacture the insert.

Viability study

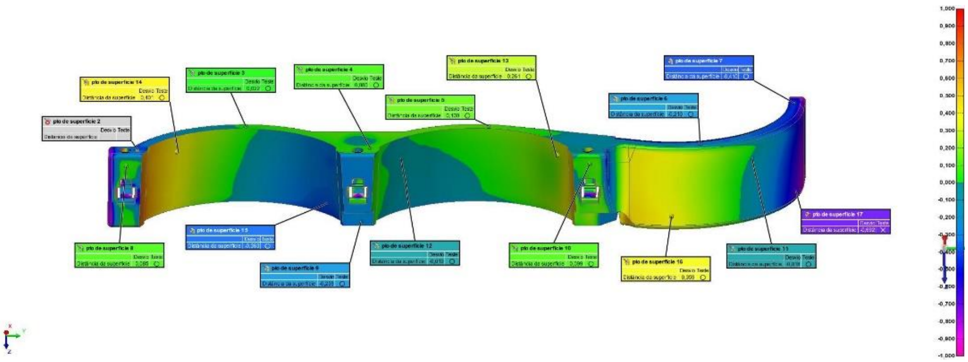
The insert was manufactured by L-PBF in its full form. The finishing operation involved milling of the base and electro-discharge machining (EDM) for the active region of the insert. According to Moldetipo, these finishing operations are similar to the ones necessary to obtain the conventional insert (without any cooling channels). The additional difference was the presence of colling inlets for the connection to the water-cooling circuit. It was not possible to determine the long-term performance of the insert, and concerns about the structural integrity derived from the cracks detected upon analysis are not to be disregarded. It would be therefore relevant to perform a thermal treatment to the insert, after L-PBF manufacturing and before the finishing operations, to produce a tougher part and perhaps avoid cracking.

The conventional and L-PBF inserts were assembled in the mould and injection tests were performed. For comparison, two cooling times were considered: 10s and 16s. Parts produced were separated into 4 groups:

- C10 - conventional insert, 10s cooling time
- C16 - conventional insert, 16s cooling time;
- S10 - L-PBF insert, 10s cooling time;
- S16 - L-PBF insert, 16s cooling time.

For the full assessment of deviations from the CAD model, 5 specimens of each of the those groups types were analysed.

Figures 11 and 12 show an example of the dimensional analysis (deviation from CAD geometry) of 2 samples of injected parts: manufactured with the L-PBF insert and manufactured with the conventional insert. Both parts had a cooling time of 16s (C16 and S16).



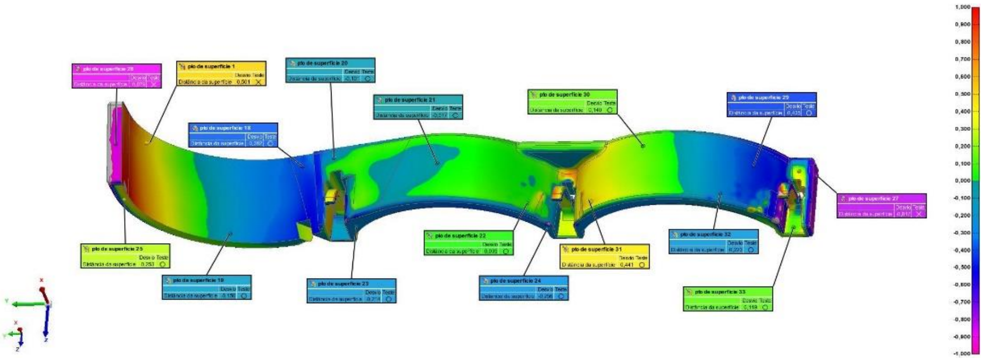


Figure 11– dimensional analysis of the parts injected with the L-PBF insert and cooled during 16s.

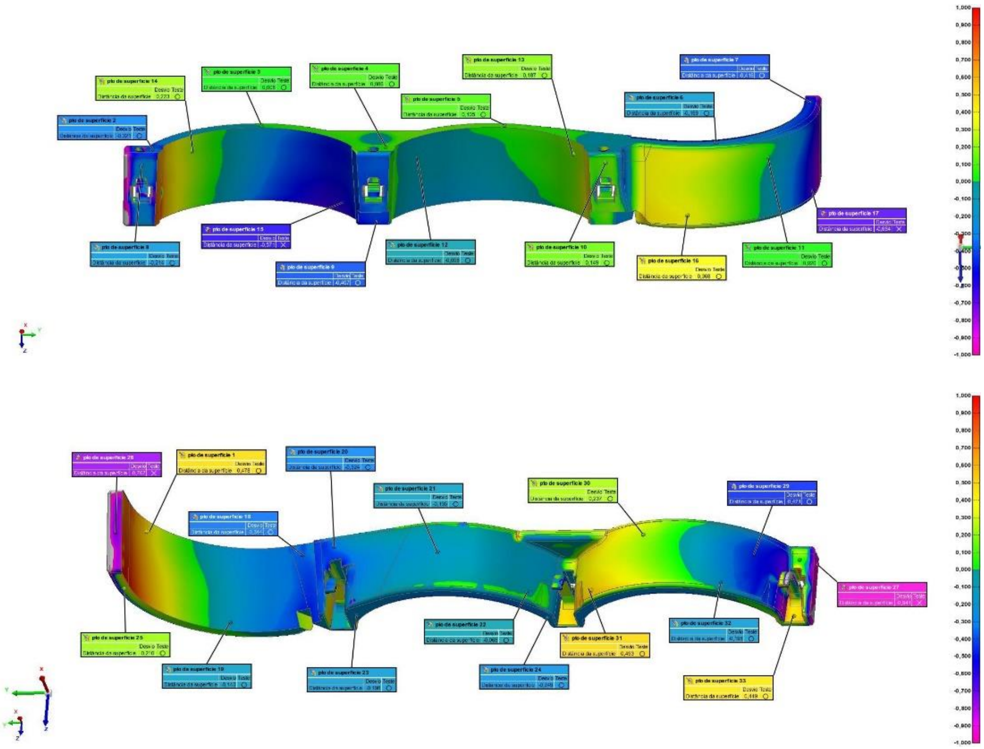


Figure 12– dimensional analysis of the parts injected with the conventional insert and cooled during 16s.

32 points were measured in each part. A detailed analysis of deviations along those points is presented on Figure 13. The summary of average deviation and average of standard deviations is shown on Figure 14. It is possible to observe that the macroscopic amount and trend of warpage is not very different amongst all specimens. However, it is possible to detect a minor degree of deviation from CAD in the L-PBF specimens (S10 and S16), although the average standard deviation is significant.

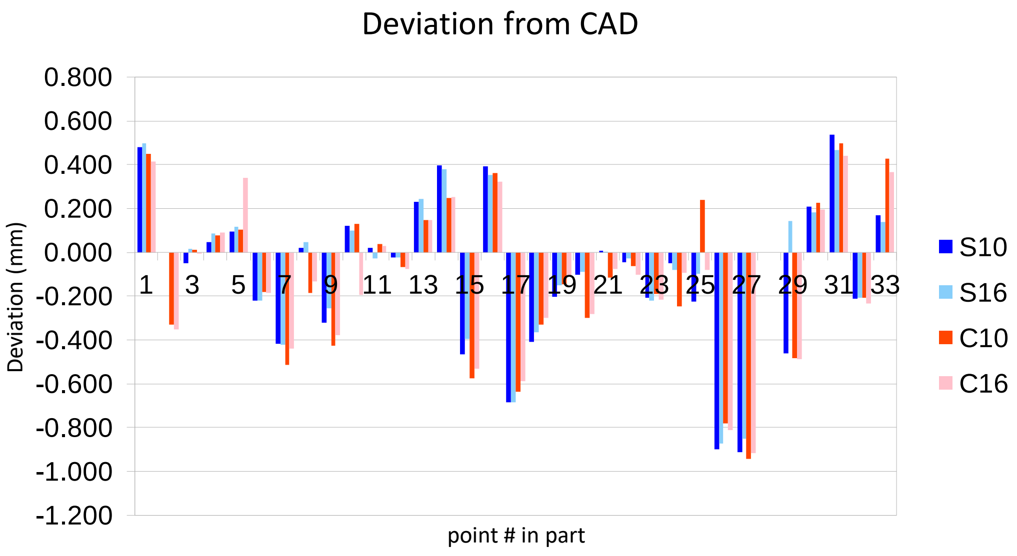


Figure 13– Average deviations in each point on the parts.

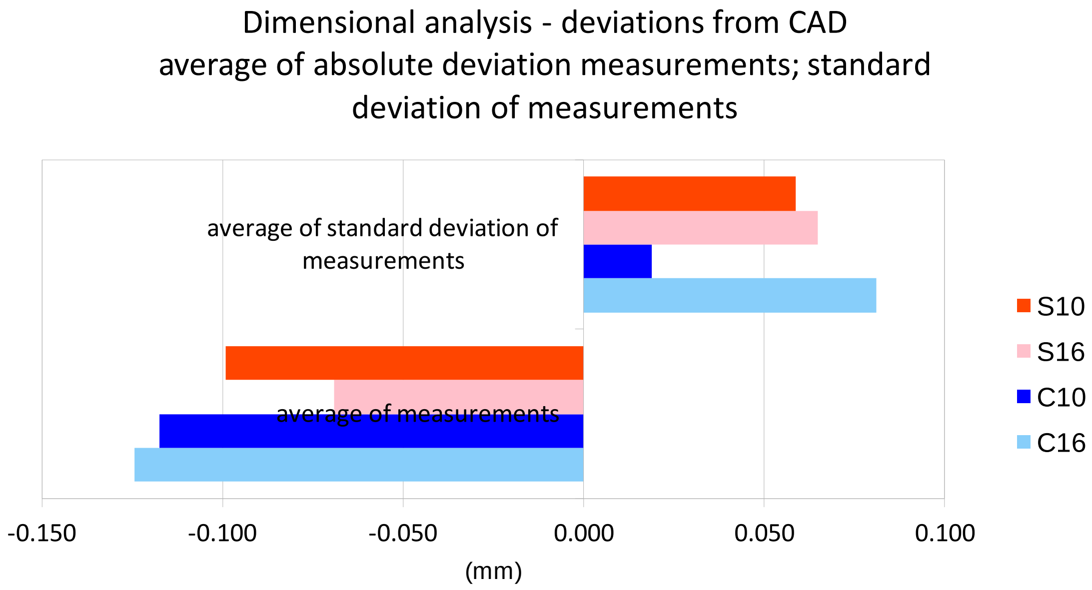


Figure 14– Average and standard deviation of measurements for all specimens

For the viability study, the internal costs of modelling and producing the L-PBF insert were compared with the same costs for the production of the conventional insert. Table 1 summarizes the cost items considered for both inserts. The detail level of each is different, as the L-PBF was manufactured internally at CDRSP and the conventional insert was manufactured at Moldetipo and hence there is a limitation of information, due to confidentiality issues.

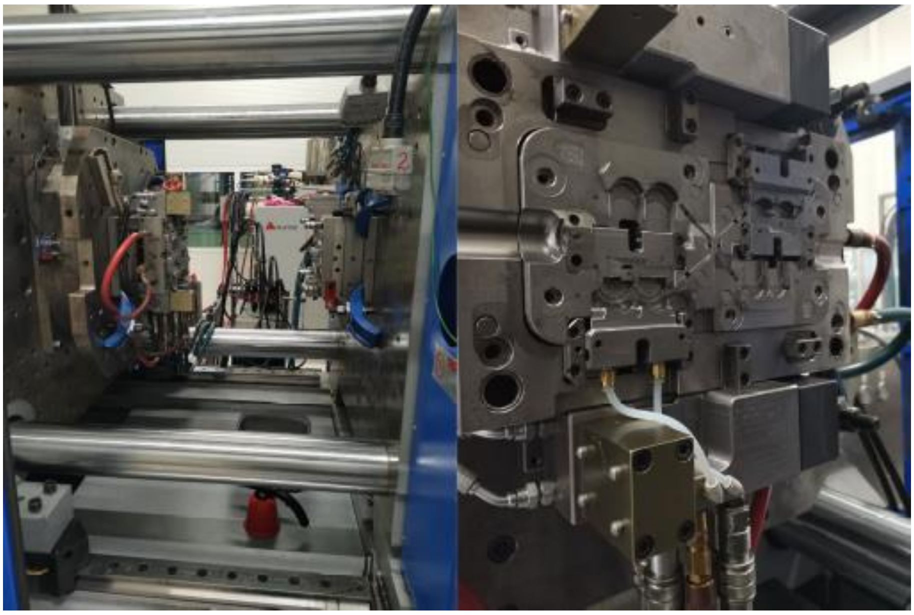


Figure 15 (left) injection mould machine with mould assembled; (right) detail of the mould cavity showing the L-PBF insert with cooling inlets attached.

	Manufacturing cost (€)	Finishing cost (€)
L-PBF insert	Materials and equipment: Powder + print time + gas + electricity + equipment deprecitation + insuccess rate – 77€ Time (considering hourly rate of 50€) Modeling and simulations + Preparation + Post processing – 925€ Total: 1002€	Milling + EDM + adjustments - 100
Conventional insert	Manufacturing - 250€	Milling + EDM + adjustments - 100
Cost difference	**752 €**	0

It can be observed that there is a cost difference of 752€, which will be used as input for the viability study.
The viability study was performed with the following parameters:

- initial cost handicap - -752€
- injection cycle time difference (less on the L-PBF insert) – 6s

• hourly cost of injection moulding machine, including operator and remaining fixed costs – 40€

Calculating the costs of production for variable batch sizes from 1000 to 100000 parts it is possible to determine the break-even of the initial cost handicap from the L-PBF insert – Figure 16. As it can be observed, a batch size of only roughly 12000 parts is sufficient for recovering the cost difference of the L-PBF insert. This is a very interesting result, as that batch size is quite small in the context of an injection moulding production task.

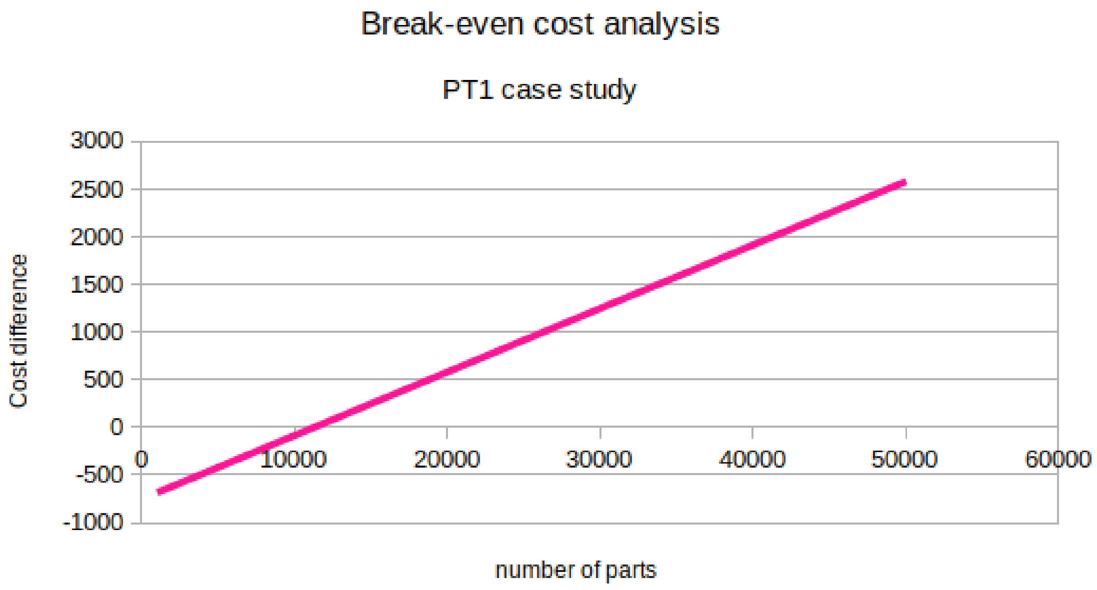


Figure 16: Break-even cost analysis for the L-PBF insert in comparison with the conventional insert.

2.3. Pilot SP1- MEUPE/INESPASA

Background

The pilot analysed on this section is a manual drilling system developed by INESPASA for the aeronautic sector (Figure 17.a). This system must be compact (no space inside besides electronic and motors) and lightweight. The Case was originally obtained by machining a block of Aluminium (material with low density and inexpensive). This compact solution had some difficulties associated with heat dissipation. During operation, heat generated by the motors produce a temperature increase where the operator needs to put his hand (Figure 17.b), till more than 60 Celsius degrees. Depending on the revolutions per minute, the motors could even stop due to hight operation temperature.

The delivery time of the entire system is 3-4 weeks and could be produced with less than 1.000€. However, the part under study is the case where the motors are located (left, Figure 17.b), and this component could be produced in 1 day (8h) and at a cost of 500€ approximately.

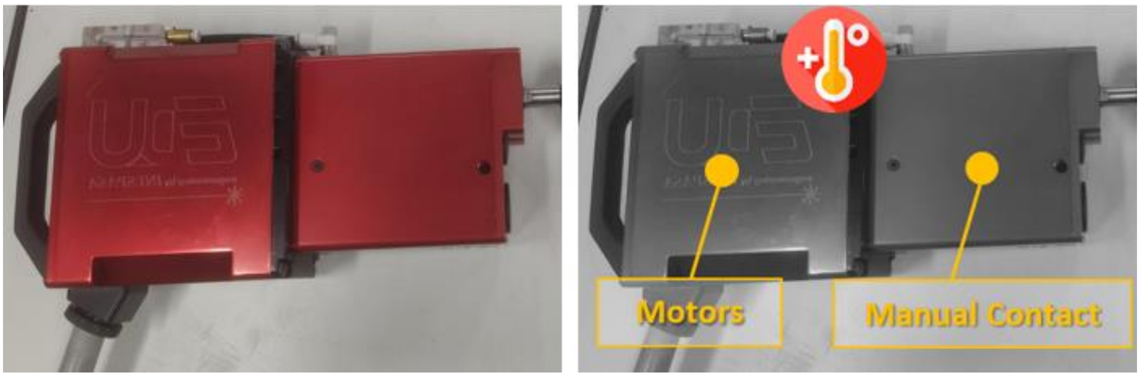


Figure 17. Image of (a) original case and (b) areas with bad thermal dissipation

Objectives of the Pilot

The main objectives of this pilot are listed below:

- Manufacture the entire aluminum case with Powder Bed Fusion Laser
- Increase the thermal performance by adding active (cooling channels inside the component) or passive heat dissipation (lattice or gyroid structure).
- Compare the thermal properties between the original machined part with the results obtain by PBFL
- Decrease the need of tooling for machining
- Seeking to optimize technology already in place adding functionality to a tool.

To meet these objectives, the MAM proposed solution was to manufacture the case where the motors are located, including internal channels to refrigerate the case and the motors (Figure 18). Since the system already had a pneumatic internal subsystem, the same air flow can be used to improve the thermal performance.

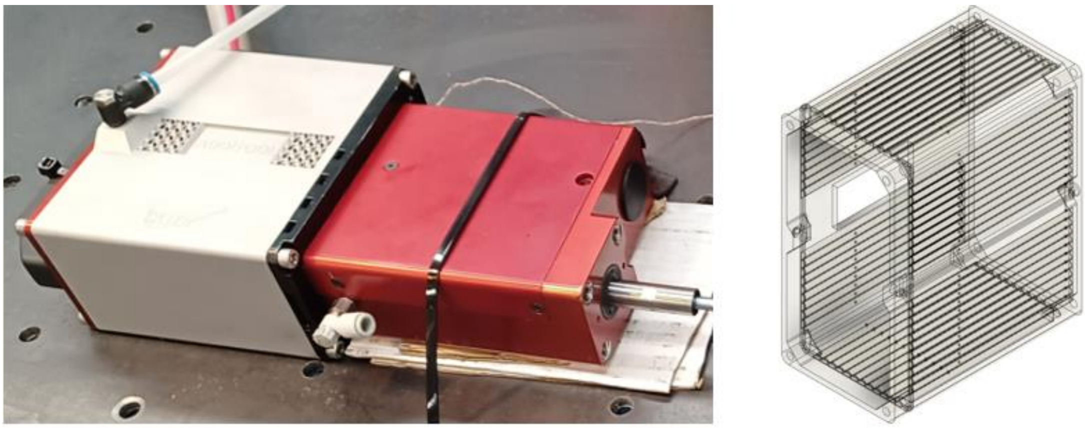


Figure 18. Image of (a) MAM case and (b) schematic view of internal channels.

Material selection

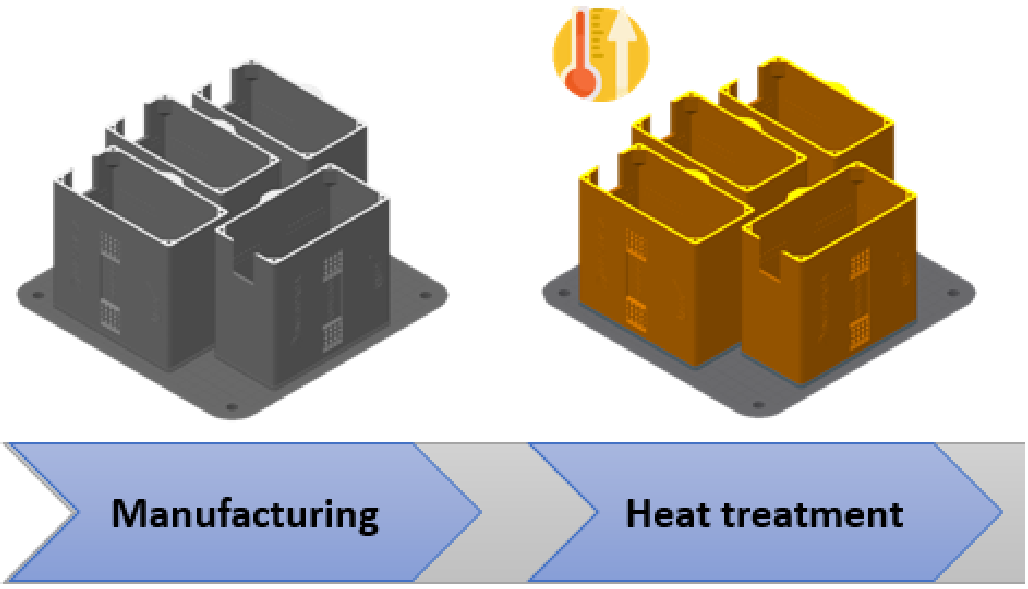
Two different materials have been study during the development of this pilot: AlSi10Mg and Scalmalloy ®.

As the main objective was to characterize electrical and thermal properties of both materials once that they are melted (solid) no characterization on the raw materials (powder) have been considered on this pilot, The information delivered by the powder supplier was considered as baseline. Scalmalloy ® powder was supplied by TOYAL and AlSi10Mg from LPW.

The results and conclusions of the selection of the material are presented in D2.1 Report on Material for MAM. As main conclusion, Scalmalloy® was selected as better approach for this pilot as it has better mechanical properties but also lower thermal conductivity.

Viability study

To study the economic viability of the proposed MAM solution, the best approach has been found by manufacturing 4 cases in one shot, using wire cutting to extract the component but also to obtain the interfaces. Holes and threads are achieved manually (Figure 19).



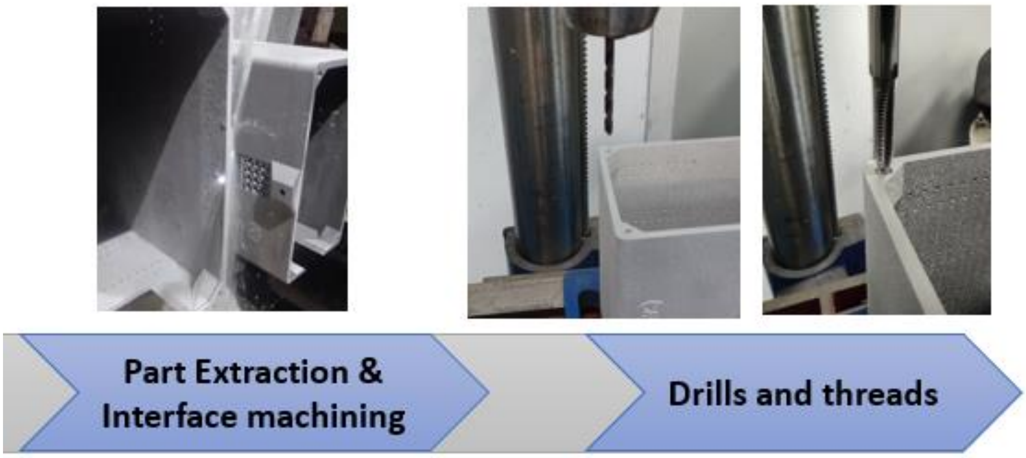


Figure 19. Road map to manufacture the MAM case.

Considering the manufacturing process presented in Figure 19, four cases could be manufactured, heat treated, wire cut, drilled, and threaded in less than 30 h (7.5h/case). The cost of each case is 750€ approximately.

Comparing conventional and MAM case, it can be observed that both haves similar delivery time, but in terms of cost, the case obtained by MAM is 250€ more expensive than the conventional one. This result was expected as the cost of machining a simple geometry of Aluminium is difficult to improve.

On the other hand, regarding technological viability, the results presented in the deliverable D 2.2.1 Report of results of manufacturing, show how the case redesign with internal channels has improved drastically the thermal performance of the entire system, reaching a difference of 31oC (55°C to 24°C) in the surface of the analysed case.

Figure below show the thermographic analysis performed on the conventional (Figure 20.a) and redesign case (Figure 20.b), after operating for 50 minutes. It can be observed how the maximum temperature reached by the MAM case is 24°C, while the conventional case achieves 55°C.

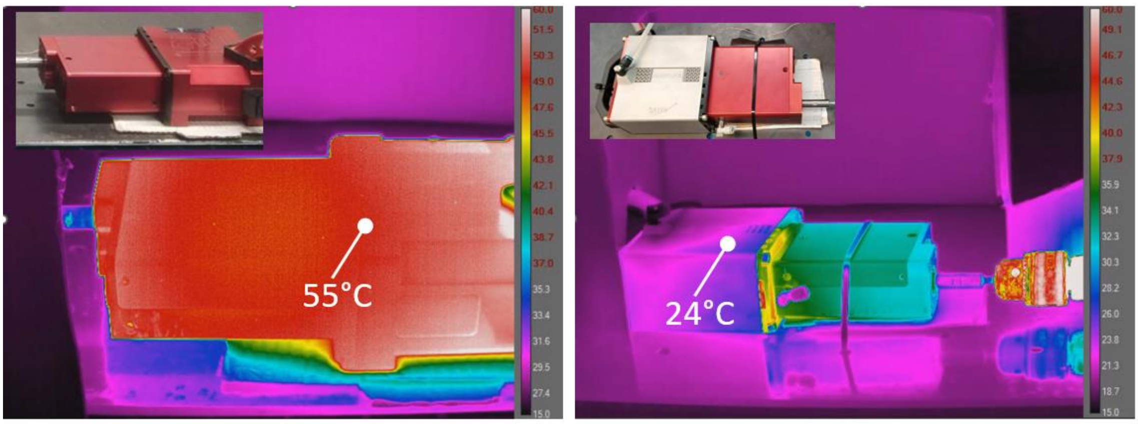


Figure 20. Thermographic images of (a) Conventional and (b) AM cases

The demonstrator has been tested together with the company INESPASA and, besides the extra cost of 250€ per case, the solution proposed during this project has clearly satisfied the enduser, as the system is now functional, with a thermal behaviour which makes the tool comfortable, lighter (37% weight reduction) and operational for long periods.

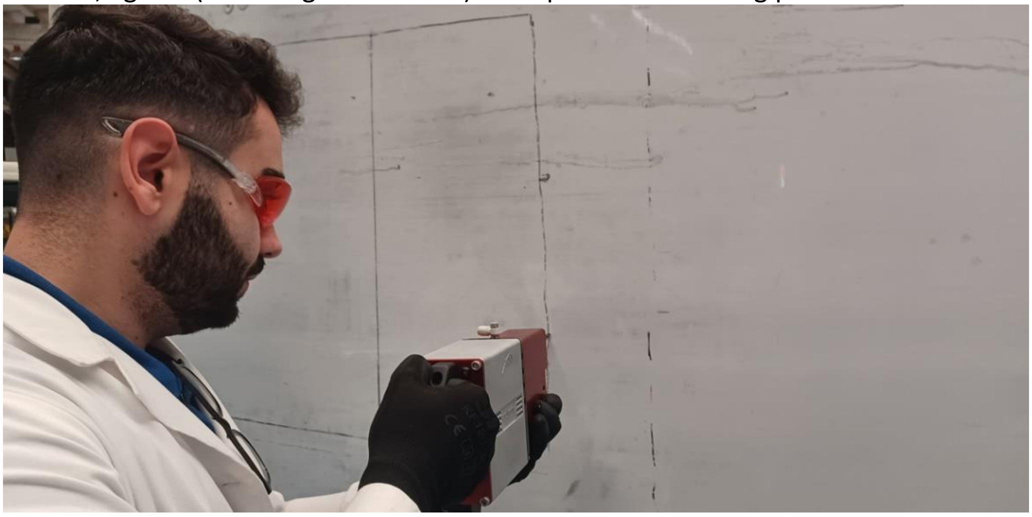


Figure 21. Image of the final test performed to validate the tool.

2.4. Pilot FR2-SOMOCAP

Background

The pilot parts offered by the associated partner SOMOCAP is a molding core for plastic injection (Polyethylene PE).

This tool, dealing with agricultural industry, is a part originally machined from a massive block of 40CMD8 steel (C45), with a 10mm hole inside to cool the polymer part all around.
However, this simply straight hole for cooling is not enough and the cooling is not efficient: during the cooling phase, the polymer part reveals an ovalization and is not quite circular.

Original datas:

- Final tolerance: +/-0.02mm polish demolding
- Original price: 5000€ (including electro-erosion for the top of the part)
- Original delivery time: 2 weeks
- Injection pressure: 800 bars

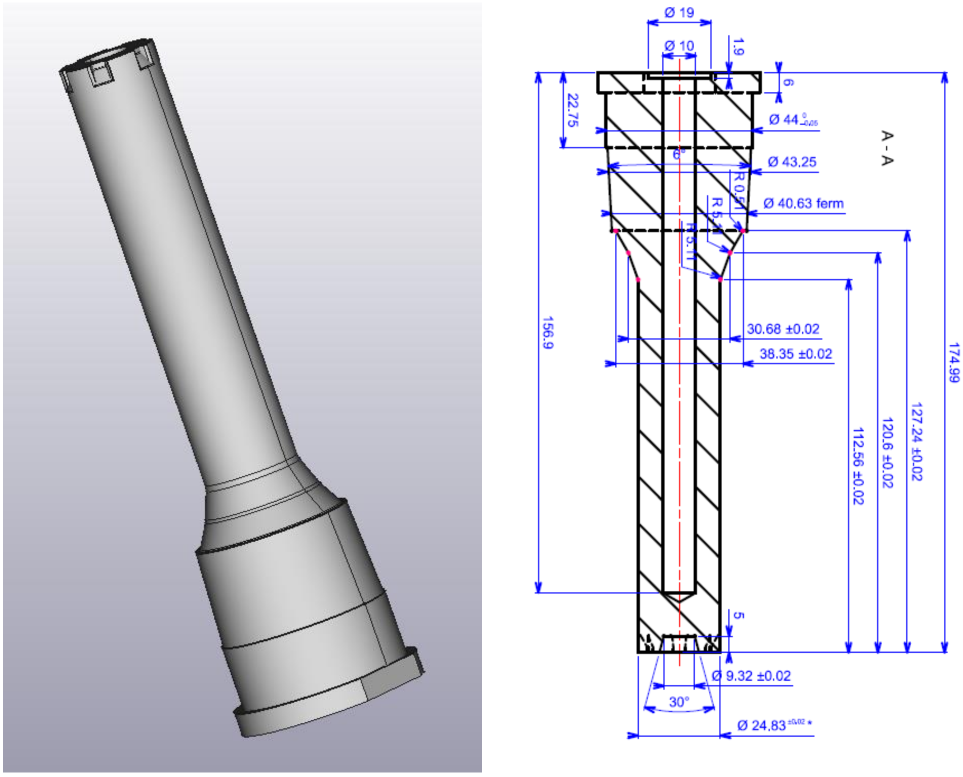


Figure 22: SOMOCAP Proposal pilot

The thermal regulation is currently done with a separator, as shown in the Figure 23.

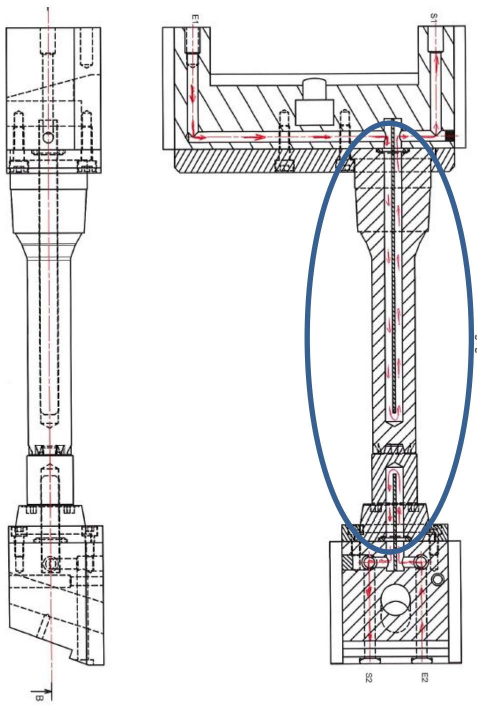


Figure 23: Principle of thermal regulation

Objectives of the Pilot

The objectives of this pilot are various:

- Manufacture this part with 2 different FFF/FDM metal charged (Fused Filament Fabrication / Fused Deposition Modelling) and sintering (with and without Hot Isostatic Pressing-HIP).
- Increase the performance of this tool by adding conformal cooling.
- Reduce delivery time and price.
- Make accessible Metal Additive Manufacturing to all / Technology based on Metal Injection Moulding (MIM) Process.

Metal Additive Manufacturing technologies, including DED Wire Laser or Arc, L-PBF, DED Powder Laser, etc. are very expensive and these costs are generally prohibitive for a SME.

Developing a new process, based on a well-known technology (FDM process) and try to have a cheaper metallic part is one of the major objectives of this pilot.

The reference on the market to do this kind of application is the Markforged Metal X, available in the ADDITOOL consortium. However, this machine is a closed system, and totally "proprietary technology".

Try to do the same work with a classic and open machine, directly available on the market could be very interesting.

A redesign of the tool proposed by SOMOCAP has been done by the ADDITOOL partners to increase the cooling performance. The pilot to manufacture is shown on Figure 24.

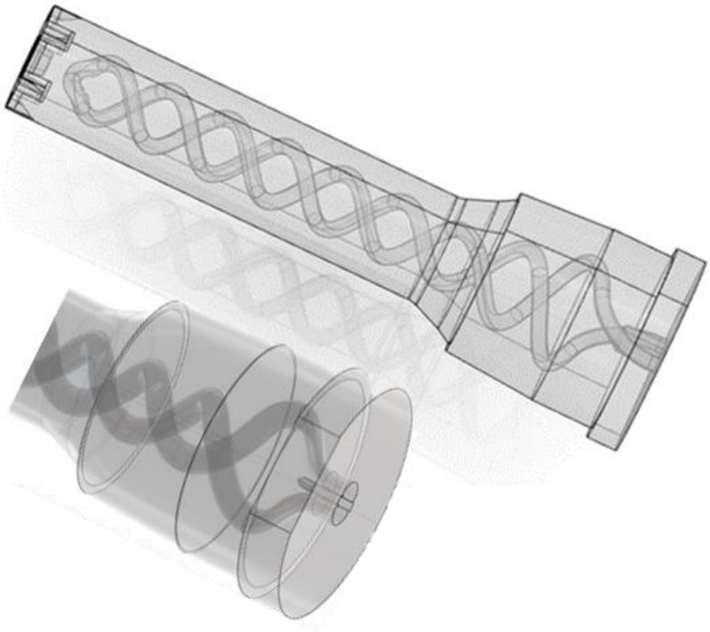


Figure 24 : Somocap pilot with Cooling channels

To meet these objectives, here is the method that was used:

- Characterize the material and the part manufactured for each technology: Raw material and manufactured material.
- Manufacture the part by different technologies: Markforged Metal X + accessories & Lynxter S600D + accessories.
- Heat treatment : Debinding / Sintering.
- 3D Scan / Tomography.
- Machining of the parts.
- Test the tools on their production site + viability deliverable.

Material selection

At the beginning of ADDITOOL, here are the materials available on the market:

- BASF: Ultrafuse 316L & Ultrafuse 17-4PH – Catalytic debinding
- Nanoé: Zetamix 316L & Zetamix H13 – Thermal debinding
- Nanovia: Mt 316L – Thermal debinding
- Markforged: 17-4PH, Copper, Inconel 625, H13, A2 and D2 tool steel. All materials are dedicated with Metal X machine and accessories –Debinding with Opteon SF-79

According to the specification gived by SOMOCAP, only the 17-4PH and the H13 answers our problematics (hardness and high-pressure condition), see Figure 25.

Also, the H13 and the 17-4PH are available as for Markforged Metal X as for an open system.

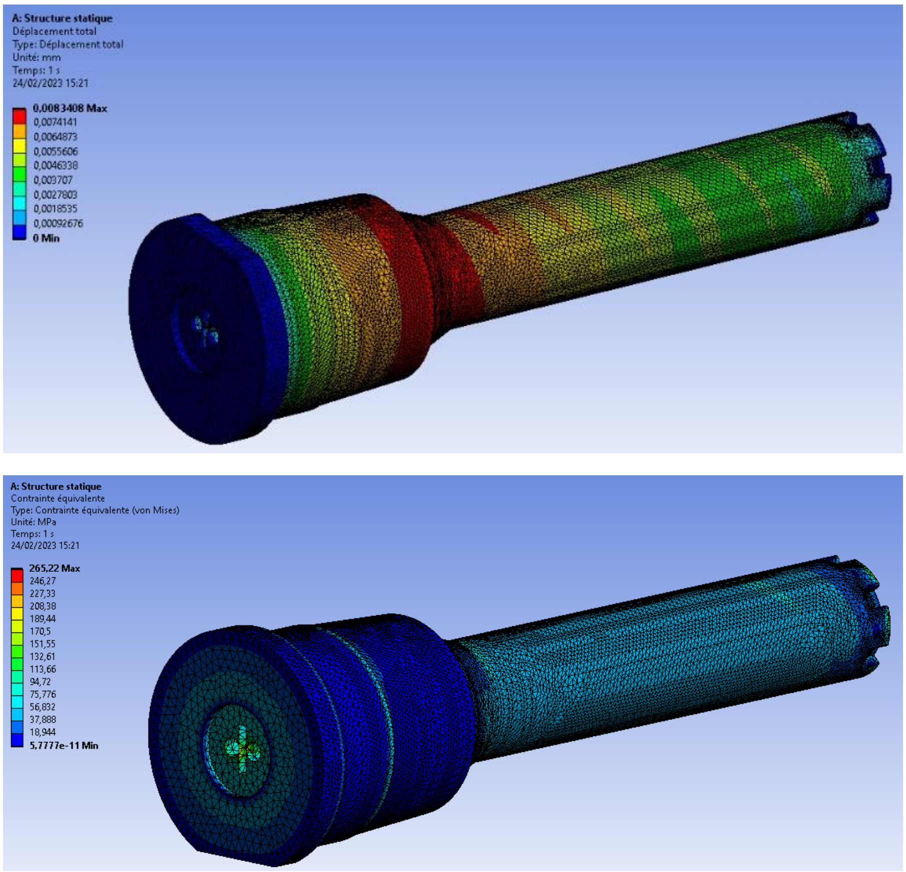


Figure 25: Simulation & Sizing according to the material

Viability study

The manufacture of the SOMOCAP part was carried out with the following means:

- Markforged Metal X + accessories
- LYNXTER S600D + accessories
- RAPIDIA technology based on aqua-paste metal charged.

Technically, the NANOE filament gives bad results; not with the printing (Lynxter S600D) but with the debinding & sintering phase if it used as it is recommended. Debinding and sintering process have been optimised by the consortium for this filament, obtaining good external geometry and controlled C levels. Final HIP cycle allowed to close most of the porosity, but it is necessary to have a first chemical debinding to open pores and facilitate the thermal debinding.

The manufacturer announced 91h of debinding / sintering process that is not acceptable for a SME and have been reduced to less than 20h, that is an interesting result.
However, relatively low metallurgical and mechanical properties forced us to stop the development for such a large part. This filament can work for small parts but is not currently viable for large and tall parts.

The Markforged Metal X, actual reference on the market, gives quite good results but a little bit under the specification announced, see Deliverable D2.1.1 Report on MAM material. Additionally, Markforged H13 was almost dense already after sintering and with HIP all the remaining pores were closed. However, dimensional restrictions still exist in the Markforged for manufacturing and sintering a large part.

Figure 26: Manufacturing with Markforged Metal X

The RAPIDIA technology seems promising insofar as it does not use a filament loaded with 50% metal powder but an aqueous paste with close to 60% solids loading, and a very low (<1%) polymer binder.
Using a feedstock with very small amounts of polymer present allows RAPIDIA to simplify the debinding and produce less emissions. The Rapidia metal 3D printing system is a system able to print parts with complex internal structures, using proprietary evaporative support technology. The water-based paste allows complex assemblies to be created with ease by water bonding 3D printed parts together, or by fusing 3D printed parts to machined parts. This metal 3D printing system allows parts to be sintered directly off the printer, with no separate debinding step. Parts printed with conventional three-stage processes need to be prepared for sintering by dissolving the polymer binder. This step can take upwards of several days and requires treating the printed part with a chemical solvent. The Rapidia process eliminates the need for a separate debinding stage by replacing most of the polymer binders with water. The water evaporates during printing, leaving a green part with less than 1% binding additives. Green parts made on Rapidia's system can go straight into sintering, with short sintering cycles - a safe process that can deliver parts faster.

Both Markforged and RAPIDIA allows a print with a wide range of metals, with options for excellent strength, high temperature capabilities, and good corrosion resistance.
The full manufacturing chain of commercial brand Markforged and Rapidia are optimised and work in hidden time which makes these technologies very competitive (production during the night for example, no need to have an operator in front of the machine, etc.).

Figure 27 : Rapidia technology

Some costs according to the raw material:

Material	Price/kg
Nanovia Mt 316	250€/kg
Nanoe Zetamix 316L	500€/kg
Nanoe Zetamix H13	500€/kg
BASF Ultrafuse 17-4PH	100€/kg
BASF Ultrafuse 316L	130€/kg
Markforged H13	245€/200cm^3
Markforged 17-4PH	135€/200cm^3
RAPIDIA 17-4PH	376€/L --> 75.2€/kg

Description	Price	Delay
Programming	56 € (900 €/day)	30min
Fabrication	150 € (150 €/day)	20h
Material – 1.8kg	156€ for 17-4PH Markforged 283€ for H13 Markforged 87€ for 17-4PH Rapidia	/
Debinding and sintering	900 €	Day +1
Machining	865 €	1 week subcontracting
Total	**2 127 € Markforged 17-4PH** **2 254 € Markforged H13** **2058 € RAPIDIA 17-4PH**	**5 days**

The cost, even if it is less important than the original is not an indicator here because the comparison with the original part is not possible.
Indeed, this process allows to manufacture the part with a real added value (the conformal cooling channel is only possible with MAM technologies) that was not possible with conventional technologies.

2.5. Pilot PT2- VIDIRIMOLDE

<u>Background</u>

The application of conformal cooling channels, designed to closely match the part geometry to enhance their cooling, has been applied to plastics injection molds, stamping dies and other tools, to allow a reduction in cycle time and / or attaining specific thermal cycles, such as quenching.
However, this has not been the case of molds for glass. These have aspects that make the application of conformal cooling channels worth studying. These are: the working temperatures – around 600ºC - , the cooling medium – compressed air -, and the cycle time – typically a few seconds.
Conventional cooling of glass molds is performed by injecting compressed air through a set of straight drilled holes that run along the vertical direction of the mold. This is called “vertiflow” – Figure 28. The advantage of this approach is the relative simplicity in achieving these holes.

The disadvantage is the temperature around the glass part is not uniform throughout the mold surface. This means there is a higher probability of defects in the final part.

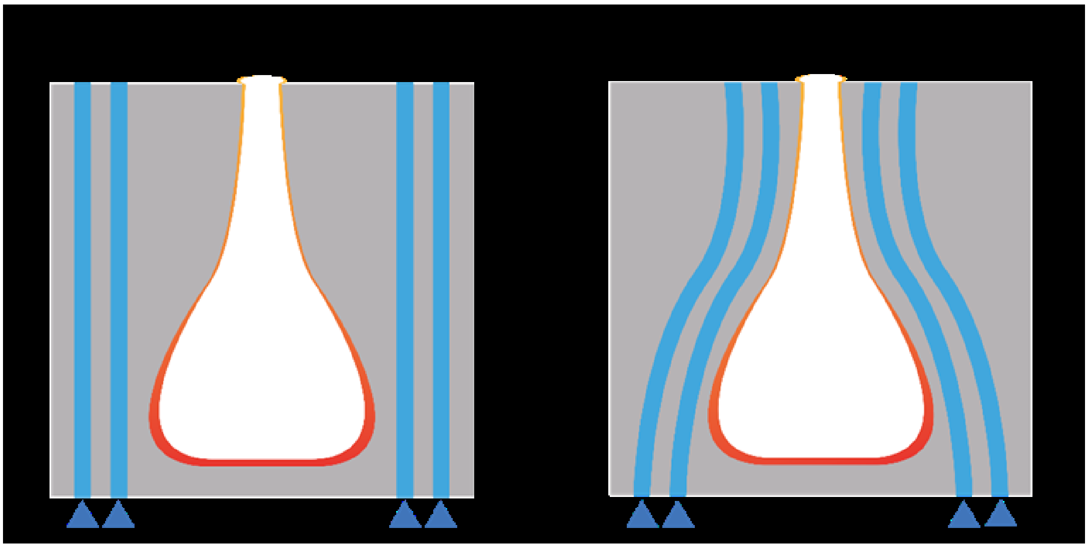


Figure 28: The two types of cooling for glass moulds. Left - the conventional cooling method; right - the proposed conformal cooling method.

Moulds for glass also have problems with wear in the moulding surfaces, due to the high service temperatures. This is usually mitigated by depositing a layer of a harder material, such as a nickel-based alloy, in the mould internal edges. This process is usually performed by plasma, TIG, or MIG deposition, as an additional process within the production line.

The part proposed is a mould for a small glass bottle – Figure 29. This bottle has an unusual geometry, which poses an additional challenge for the conventional cooling system. However, given its small dimension, it will be more appropriate for producing by AM.

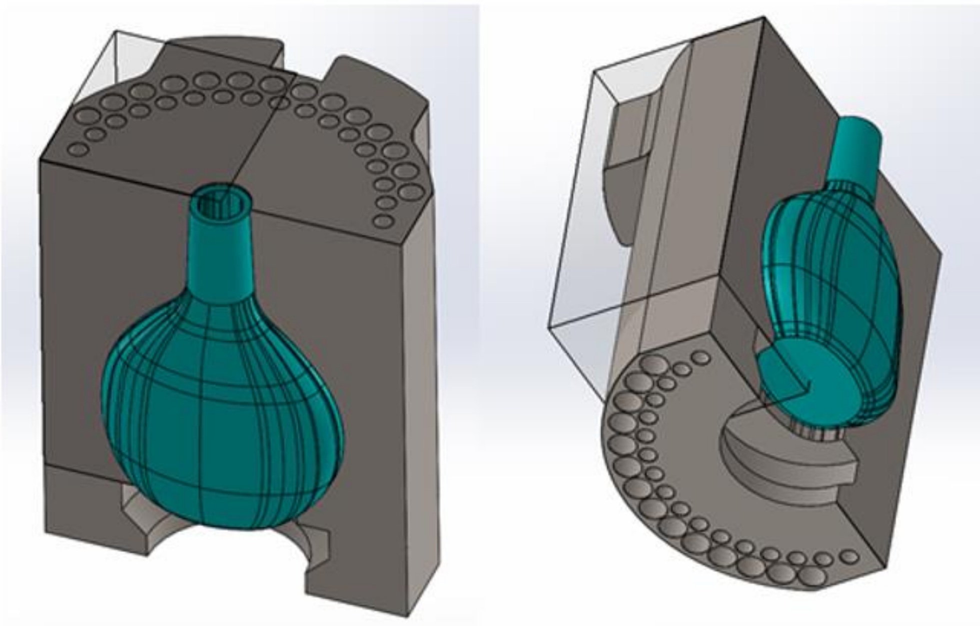


Figure 29: A mould for a glass bottle.

Objectives of the Pilot

The objective of the pilot is to assess the viability of applying a conformal cooling system to the mold, while combining it with an internal lattice structure for weight reduction and with an enhanced molding surface. The first two objectives are achieved by using L-PBF manufacturing, while the last is achieved by depositing layers of nickel alloy by DED Laser powder.

Material selection

The material selected for the pilot is a commercial stainless steel in powder form - EOS Stainless Steel CX. This is because the part will be manufactured at a partner company, due to its size, and this is the powder (SS) they had available in the equipment.

Viability study

The mold was first manufactured by L-PBF, leaving an offset surface for the subsequent deposition by L-DED. The finishing operation involved milling of the molding surface.

It was not possible to test the mold in real working conditions. This is because that would require stopping a production line and replacing a set of molds in a station (usually comprised of about 12 molds). Thus, indications on the cooling performance were drawn from model tests. In these, a set of specimens for several cooling systems options were tested using compressed air, after being heated at the typical service temperatures. These options included channels with circular section, elliptical section, combined with non-uniform sections along the length of the specimen, as well as the combination with lattice structures and internal fins - Figure 30.

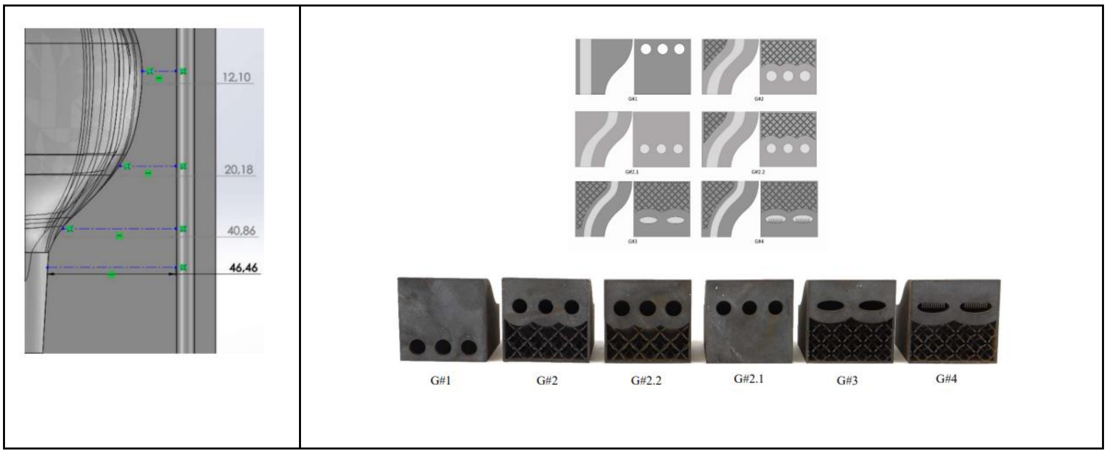


Figure 30: The specimens geometry for the cooling modelling.

Results indicate that all conformal cooling solutions achieve a faster cooling rate when compared to the conventional cooling solution. For a 650ºC starting temperature, the best performing conformal cooling solution – G#3 (elliptical channels combined with a lattice structure) – reduces the cooling time to attain, for instance, 610ºC to approximately half (from about 9s to 4,5s) – Figure 31.

The internal costs of modeling and producing the L-PBF mold were compared with the same costs to produce the conventional mold. Table below summarizes the cost items considered for both molds.

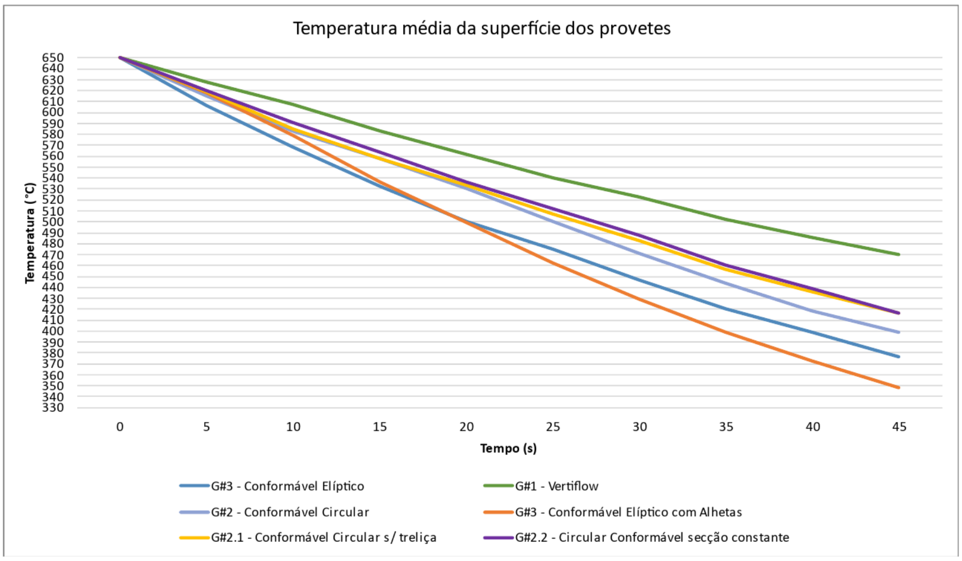


Figure 31: Comparison of cooling performance from conventional cooling and several conformal cooling options. Average temperature at the specimens surface (the mould surface)

	Manufacturing cost (€)	Finishing cost (€)
L-PBF manufacturing	Estimated cost:10000€	Milling - 100€
DED deposition	Estimated cost: 5000€	
Conventional mould	Estimated cost: 280€	Milling - 100€
Cost difference	**14720**	**0**

For the calculation of the number of parts necessary to compensate for the initial cost difference, the following parameters were considered:

- initial handicap cost: **14720€ - 1 mould;**
- in a production setting, each machine operates between 8 to 12 moulds. It is considered 10 moulds per machine for this scenario. This elevates the initial cost difference to **147200€**
- for the part cycle time, a base value of **3s** was considered
- for the cycle time reduction (gain), two scenarios were considered:
    - 25% reduction (new cycle time=2,25s) and
    - 50% reduction (new cycle time=1,5s). These were based on the simulations previously presented.
- The hourly rate of the machine / operator / installations was considered 80€ (estimation)
- The production rate was considered **15 parts/minute per mould, or 150 parts/minute for the set of 10 moulds**
- The production line was considered to be operating continuously (24h)
- Given the above parameters, it is possible to calculate the number of parts that compensate the initial cost handicap for both scenarios:
- for 25% reduction in cycle time – 883200 parts. Considering the production rate, this means 41 days.
- for 50% reduction in cycle time – 441600 parts. Considering the production rate, this means 21 days.

As it is observable, although the initial cost for implementing 10 L-PBF + DED moulds in a production setting is very high – roughly 15000€ - the fact that the glass industry works with high production rates means the payback time is not as high as one may expect. Although the costs are not fully determined, as no more detailed information was possible to access, it is reasonable to say that there is potential viability for the usage of MAM technologies in the glass manufacturing sector.

3.CONCLUSIONS

The results presented on this documents has shown a potential viability for the usage of MAM technologies in the tooling sector. 5 different pilots (FR1, PT1, SP1, FR2, PT2) have been developed for this wide sector (mould for plastic, mould for glass, machining, control jigs...) by using different MAM technologies (PBF-L/M, DED Wire Laser, DED Wire Arc, DED Power Laser and FFF).

Technological viability has been demonstrated by testing the pilots in real conditions. All of them has shown good results fulfilling the requirements (excluding PT2 as this test requires to stop the production line, hence it will be tested in coming programmed stoppages).

In terms of the economical viability study, different conclusions have been found depending on the studied pilot (see conclusions of each pilot). In general, delivery time has been reduced by using MAM technologies. Regarding cost, it can be observed that the subcontracting of machining have a big impact on the total cost. This increment should decrease if more training to machine Near Net Shape is performed.

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